Search for Leptoquarks with the D0 detector

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We report on D0 searches for leptoquarks (LQ) predicted in extended gauge theories and composite models to explain the symmetry between quarks and leptons. Data samples obtained with the D0 detector from $p\bar{p}$ collisions at a center-of-mass energy of 1.96 TeV corresponding to intergrated luminosities of 1–4 fb^{-1} were analyzed. No evidence for the production of such particles were observed and lower limits on leptoquark masses are set.

1. Introduction

Current theories [1] suggest that leptoquarks would come in three different generations corresponding to the three quark and lepton generations. Leptoquarks would have color, fractional electric charge, both lepton and baryon numbers, and could be scalars or vectors. At the Tevatron leptoquarks could appear in pairs through $q\bar{q}$ annihilation (dominates for $M_{LQ} > 100$ GeV) or gg fusion,

$$p + \bar{p} \rightarrow LQ + \overline{LQ} + X$$

or through the associated lepton production

$$p + \bar{p} \rightarrow LQ + \bar{l} + X$$

with the contribution of the last one being small. The pair production cross section for scalar leptoquarks only depends on the strong coupling constant and on the leptoquark mass. The vector leptoquark pair production cross section also depends on anomalous $LQ - gluon$ couplings k_G and λ_G, and the experimental constrains are generally given for three models: "Minimal Coupling" ($k_G = 1$, $\lambda_G = 0$), "Yang Mills" ($k_G = 0$, $\lambda_G = 0$), and "Minus Minus" ($k_G = -1$, $\lambda_G = -1$).

Leptoquarks decay into a charged lepton and a quark with a branching fraction β or into a neutrino and a quark with a branching fraction $(1 - \beta)$. Thus frations of a leptoquark pairs into the $llqq$, $l\nu qq$ and $\nu\nu qq$ final states are β^2, $2\beta(1 - \beta)$ and $(1 - \beta)^2$ respectively.

This report presents a summary searches for leptoquark pair production in the data sets collected with the D0 detector [2] during Run II (started March 2001) of the Fermilab Tevatron Collider.

2. Generation independent leptoquark search.

A search explored the final state where both leptoquarks decay into a neutrino and quarks assuming $\beta = 0$: $LQ\overline{LQ} \rightarrow \nu\bar{\nu}jj$. The corresponding detector signature is two acoplnar jets accompanied by missing energy. No selection specific for jet flavor were applied. Thus the search results applied to all three generations of leptoquarks. The analysis used 2.5 fb^{-1} of D0 Run II data.

Events were recorded using triggers requiring two acoplanar jets and large missing transverse energy, $\slashed{E}_T$, or large $\slashed{H}_T$, the vector sum of the jets transverse energy $\slashed{H}_T \equiv |\sum_{jets} \vec{p_T}|$. The two leading jets were required to be in the central region $|\eta| < 0.8$ of the D0 detector and have transverse momenta greater then 35 GeV. The multijet QCD background was suppressed by requiring $\slashed{E}_T$ to be greater then 75 GeV and with cuts on angular correlations between jets and $\slashed{E}_T$ directions: the azimutal angle between $\slashed{E}_T$ and the first jet and the minimal and maximal angles between any jets and $\slashed{E}_T$. To suppress the dominant standard model (SM) background from $W(\rightarrow l\nu) + jets$ events a veto on events containing an isolated electron or muon with $p_T > 10$ GeV was applied, and events with an isolated track $p_T > 5$ GeV were also rejected. The two final cuts on $\slashed{E}_T$ and $H_T = \Sigma_{jets}\ p_T$ were optimized for different signals by minimizing the expected upper limit on the cross section in the absence of signal

Table I shows the number of data, background and signal events after all selections for $M_{LQ} = 140$ GeV and $M_{LQ} = 200$ GeV leptoquark signals. No significant excess of data over the predicted backround was found. Figure 1 shows the observed and expected 95% C.L. limits on scalar leptoquark pair production cross sections as a function of the LQ mass. The observed and expected lower LQ mass limit of 214 GeV and 222 GeV respectively were obtained at the intersection of the experimental cross section limits with the nominal theoretical production cross section calculated for the factorization and renormalization scale $\mu = M_{LQ}$.

3. Search for pair production of first generation leptoquarks

A search for pair production of first generation leptoquarks was performed with 1 fb^{-1} of data on the final states with two electrons and two jets ($LQ\overline{LQ} \rightarrow eejj$, $\beta = 1$), or one electron, two jets and $\slashed{E}_T$

Table I $LQ\overline{LQ} \to \nu\bar{\nu}jj$ analysis. Number of data, background and signal events after all selections for different LQ signals.

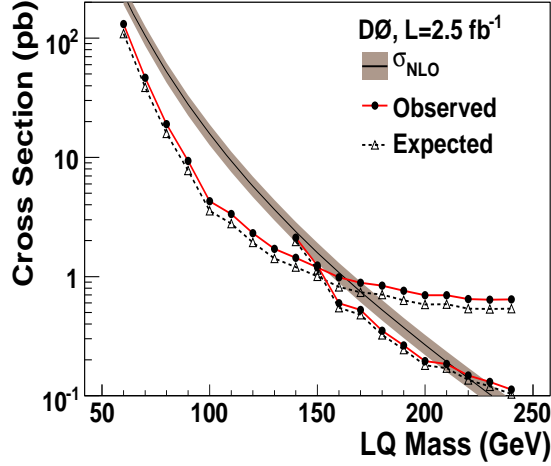| M_{LQ} GeV	$(\not{E}_T, H_T)$ GeV	Data	Background	Signal
140	(75,150)	352	$328\pm 11^{+56}_{-57}$	$229\pm8^{+24}_{-23}$
200	(125,300)	12	$10.6\pm1.7^{+4.0}_{-2.0}$	$13.7\pm0.6^{+1.8}_{-2.0}$

Figure 1: Exclusion observed (circles) and expected (triangles) 95% C.L. limits for the generation independent leptoquark search. The two graphs correspond to the low and high mass selections. The nominal NLO production cross section is shown with shaded bands corresponding to the uncertainties due to choice of the parton distribution functions (PDFs) and variations of μ from $0.5 \times M_{LQ}$ to $2 \times M_{LQ}$ added in quadrature.

$(LQ\overline{LQ} \to e\nu jj, \beta = 0.5)$. Data samples were collected with combinations of single electron and electron plus jet triggers.

In the $eejj$ analysis the selected events were required to have at least two isolated electrons with $p_T > 25$ GeV (one of the electrons should be detected in $|\eta| < 1.1$) and at least two jets with $p_T > 25$ GeV in the $|\eta| < 2.5$ region. The dielectron invariant mass M_{ee} and the transverse scalar energy S_T (the scalar sum of the momenta of the two electrons and the two highest E_T jets) were used as discriminant variables against the background processes dominated by $Z/\gamma \to e^+e^-$ events. The best sensitivities to leptoquark signals (with (20–23)% acceptances for LQ masses in 250–300 GeV range) were obtained with $S_T > 400$ GeV and $M_{ee} > 110$ GeV. No data events remained after all selections compared to the estimated backround of $1.51 \pm 0.12(stat) \pm 0.04(syst)$ events.

In the $e\nu jj$ analysis events were required to have $\not{E}_T > 35$ GeV, one isolated electron with $p_T^e > 25$ GeV

in $|\eta| < 1.1$, and at least two jets in the $|\eta| < 2.5$ region with $p_T > 40$ GeV (leading jet) and $p_T > 25$ GeV (second leading jet). A veto on a second electron was applied to avoid overlap with the $eejj$ selections. Cuts on $\not{E}_T$, p_T^e, $M_T(e, \not{E}_T)$ (the transverse invariant mass of the electron and $\not{E}_T$) were optimized against the best expected 95% C.L. limit on signal cross section. After requiring $\not{E}_T > 80$ GeV, $p_T^e > 80$ GeV, $M_T(e, \not{E}_T) > 130$ GeV eight events remained in data, while the background estimation gave $9.8 \pm 0.8 \pm 0.8$. The dominant background contributions are from $W(\to l\nu) + jets$ and $t\bar{t}$ processes. Signal acceptances varied between (18.5–20)% for LQ mass in the range 250–300 GeV.

For both the $eejj$ and $e\nu jj$ channels no deviation from the SM predictions were found and the lower 95% C.L. limits on a scalar LQ mass of 299 GeV and 284 GeV respectively were set. These two analysis were combined with the 2.5 fb^{-1} $\nu\nu jj$ search, and limits on LQ mass was determined for different values of β. Figure 2(a) shows the observed and expected LQ mass limits in the (β, M_{LQ}) mass plane.

Vector leptoquarks mass limits were obtained using the leading order theoretical production cross section with the renormalization scale $\mu = M_{LQ}$. Acceptances for vector leptoquarks are similar to thouse for scalar leptoquarks with the same M_{LQ} and the same selection as in scalar $eejj$ and $e\nu jj$ analyses were applied. Figure 2(b) shows combined limits on vector leptoquark mass for different couplings in the (β, M_{LQ}) mass plane. For $\beta = 0.5$ the 95% C.L. lower limits on first generation vector leptoquarks masses are correspondingly 357 GeV, 415 GeV and 464 GeV for the Minimal, Yang-Mills and Minus Minus couplings.

4. Search for pair production of second generation scalar leptoquarks

A search for $\mu\mu jj$ and $\mu\nu jj$ final states was made with 1 fb^{-1} data sample. The events were collected with a combination of single muon triggers.

In the $\mu\mu jj$ analysis events were required to have at least two muons with $p_T > 20$ GeV and at least two jets with $p_T > 25$ GeV. The invariant mass $M(\mu, \mu)$, reconstructed from the two muons of highest p_T and the S_T (the sum of two leading jets and the two leading muons transverse momenta) were required to be greater 100 GeV and 200 GeV, respectively. No excess of data over the SM backgrounds (dominated by $Z(\to \mu\mu) + jets$ events) was observed after these selections. The multijet background in this final state is negligible. The $M(\mu, \mu)$, S_T and four muon-jet invariant masses $M(\mu_i, jet_i)$ were used in a neural net (NN) trained separately for the each of analyzed LQ signals and SM background samples. The bin edges of the NN
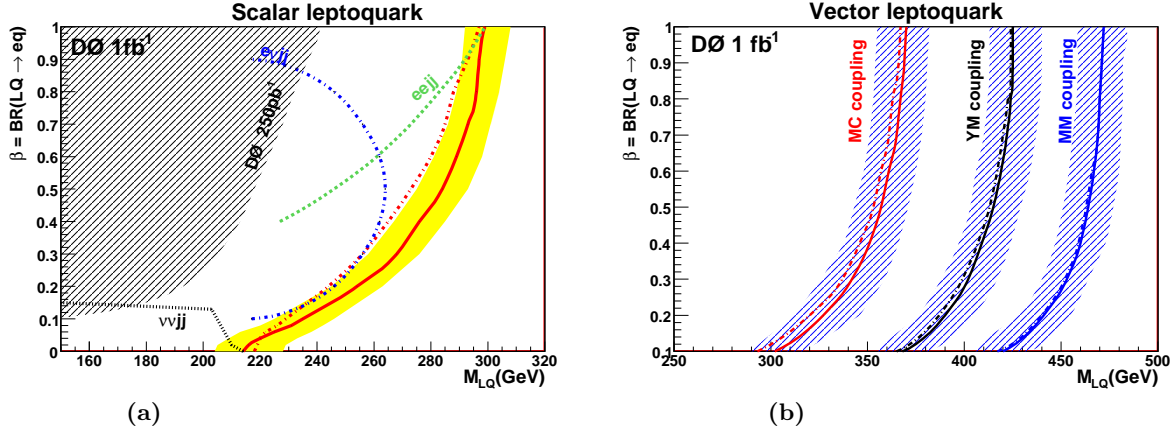
Figure 2: a) The observed (red solid line) and expected (red dot-dashed line) 95% C.L. first generation scalar leptoquarks mass limits in the (M_{LQ}, β) plane. The yellow band corresponds to the uncertainties due to the choice of the PDFs and variations of the renormalization scale on the observed limits. Also shown are the observed limits individually obtained with the 1 fb^{-1} $eejj$ and $e\nu jj$ and 2.5 fb^{-1} $\nu\nu jj$ analysis. The hatched region was excluded by the previous D0 search with a 250 pb^{-1} dataset. b) The observed (solid lines) and expected (dot-dashed lines) 95% C.L. first generation vector leptoquark mass limits in the (M_{LQ}, β) plane shown for different $LQ - gluon$ couplings. Regions to the left of the curves are excluded. The hatched bands correspond to the uncertainties due to the choice of the PDFs and variations of the renormalization scale on the observed limits.

output discriminant were chosen to concentrate background events into a few bins while the remaining bins have a significant signal to background ratio. All bins were then treated as individual channels in the calculation of the cross section limits. This method allows optimize signal sensitivity using the shape of the NN discriminant without cutting on it.

The $\mu\nu jj$ decay channel gives a $\mu\not{E}_T jj$ signature. The main background are $W(\to \mu\nu) + jets$ production and multijet events in which a jet is misidentified as an isolated muon. Events were required to have $\not{E}_T > 30$ GeV, exactly one muon with $p_T > 20$ GeV, and at least two jets with $p_T > 25$ GeV. To suppress multijet backrounds and remove events with mismeasured muon p_T the transverse mass $M_T(\mu, \not{E}_T) = \sqrt{2p_T(\mu\mu)\not{E}_T(1 - cos(\Delta\phi(\mu, \not{E}_T))}$ was required to be greater then 110 GeV and the azimutal angle between the $\not{E}_T$ and the muon was constrained to be smaller then 3.0 radians. The $S_T = p_t^\mu + p_T^{jet1} + p_T^{jet2} + \not{E}_T$ was required to be greater 200 GeV. Data were found to agree with the estimated background. The $M_T(\mu, \not{E}_T)$, S_T, two transverse masses $M(\not{E}_T, jet_i)$, and two invariant masses $M(\mu, jet_i)$ were used to calculate a neural net discriminant for each analyzed leptoquark mass and for different β values.

Figure 3(a) shows the observed and expected 95% C.L. limits for second generations scalar leptoquark pair production cross section for $\beta = 1$, and $\beta = 0.5$ as functions of M_{LQ}. The observed 95% C.L. exclusion regions in the (M_{LQ}, β) plane for $\mu\mu jj$ and $\mu\not{E}_T jj$ selections and their combinations are shown in Figure 3(b). For $\beta = 1$, $\beta = 0.5$ and $\beta = 0.1$ combined analyses excluded second generation leptoquarks with

masses $M_{LQ} < 316$ GeV, $M_{LQ} < 270$ GeV and $M_{LQ} < 185$ GeV (using the lower bound of the NLO theory)

5. Searches for pair production of third generation scalar leptoquarks

Third generation leptoquarks would decay into a b or t quarks and to a τ or tau neutrino depending on their electric charge. The τb decay is possible for LQ with charge 2/3 or 4/3 (section 5.1) and charge 1/3 LQ will decay to $\nu_\tau \bar{b}$ quark (section 5.2). The $t\tau$ and $t\nu_{tau}$ decays are suppressed due to large top quark mass. Both analysis used a neural net b-tagging tool based on the D0 tracker information to increase the signal sensitivity.

5.1. Search for $LQ\overline{LQ} \to \tau\tau b\bar{b}$

A search was conducted for $\tau^+\tau^- b\bar{b}$ final state where one of the τ decays hadronically and the other through $\tau \to \mu\nu\nu$. Thus the event signature is two b-jets, an isolated muon, a τ candidate, and missing transverse energy. A 1 fb^{-1} dataset was collected with a set of triggers required either a single muon or a muon in association with jets.

Neural networks were formed to identify hadronic tau candidates (τ_h) with calorimeter and track information for each of three possible decay modes: $\tau^\pm \to \pi^\pm\nu$, $\tau^\pm \to \pi^\pm\pi_s^0\nu$, and $\tau^\pm \to \pi^\pm\pi^\pm\pi\mp\pi_s^0\nu$. Events were required to have exactly one isolated muon with $p_T > 15$ GeV, at least two jets with
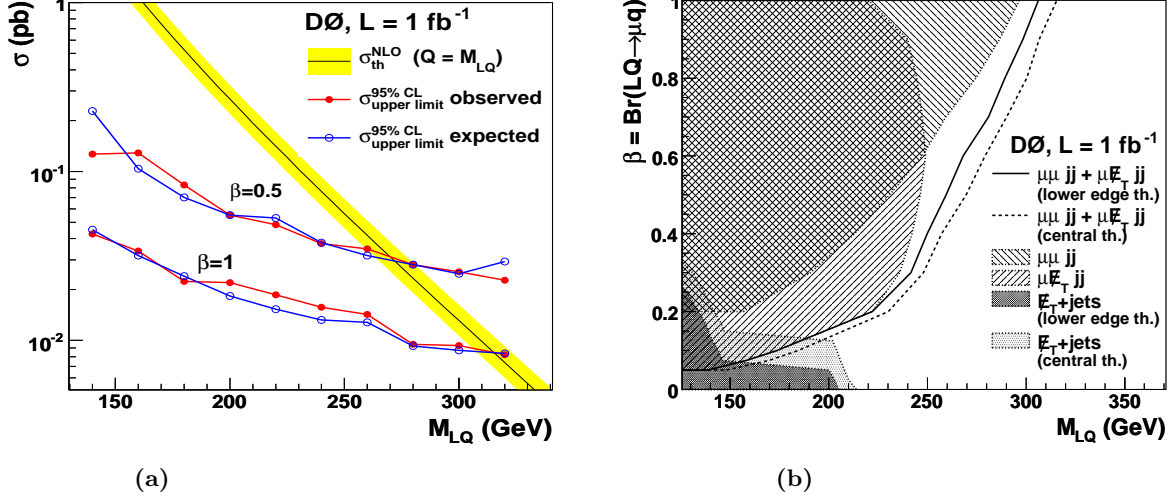
Figure 3: a) The observed (red lines) and expected (blue lines) 95% C.L. cross section limits for second generation scalar leptoquark pair production for $\mu\mu jj$ and $\mu\nu jj$ final states. The nominal NLO production cross section is shown with shaded bands corresponding to the uncertainties due to choice of PDFs and variations the factorization and renormalization scale. b) The observed 95% C.L. excluded regions in the (M_{LQ}, β) plane for $\mu\mu jj$ and $\mu\nu jj$. The region to the left of the solid line is excluded by the combination of these analyses obtained using the lower bound of NLO theory for which variation of the renormalization scale $\mu = +2M_{LQ}$ and the PDF errors were used. The dashed line corresponds to the exclusion with the nominal NLO predictions. At small β the exclusion region based on 2.5 fb^{-1} $\nu\bar{\nu}jj$ search is also shown.

$p_T > 20$ GeV, a τ_h candidate with $p_T > 15$–20GeV. and no electrons with $p_T > 12$ GeV. After these selections the estimated backround is dominated by multijet QCD events, events from $W/Z + light\ jets$ processes, and from $t\bar{t}$ production. To increase sensitivity to LQ signal the m^* parameter defined as $m^* = \sqrt{2E^\mu E^\nu(1 - cos\Delta\phi(\not{E}_T, \mu))}$, $E^\nu = \not{E}_T(E^\mu/p_T^\mu)$ was required to be less then 60 GeV. Remaining events were divided in two subsamples with one or ≥ 2 b-tagged jets. Table II shows the number of data, backround and signal ($M_{LQ} = 200$ GeV) events after different selections. No excess above the expected background were observed. Limits on LQ productions cross section were set using distributions of the $S_T = p_T^\mu + p_T^\tau + p_T^{jet_1} + p_T^{jet_1}$ parameter which is in average higher for the signal events. Figure 4 shows 95% C.L. cross section limits as a function of the LQ mass. The obtained lower limit on third generation leptoquark mass of 210 GeV (207 GeV if $t\nu_\tau$ decay is possible) is the most stringent for this decay mode to date.

5.2. Search for third generation leptoquark pairs in acoplanar b-jet events

A search was made for $LQ\overline{LQ} \to \nu\bar{\nu}b\bar{b}$. The corresponding detector signature is two acoplanar b-jets from the b-quarks and the missing energy due to es-

Table II $LQ\overline{LQ} \to \tau\tau b\bar{b}$ analysis. Number of data, background and signal ($M_{LQ} = 200$ GeV) events after different selections.

Source	$m^* < 60$ GeV	1 b-tag	≥ 2 b-tags
Data	94	15	1
Backround	109.2±5.7	19.6±2.5	4.8±0.1
LQ signal	7.4±0.1	3.4±0.1	2.6±0.1

caping neutrinos. The data sample was collected using jet plus missing energy triggers and corresponds to an integrated luminosity of 4 fb^{-1}.

Events were required to have $\not{E}_T > 40$ GeV, exactly two or three jets of $p_T > 20$ GeV ($p_T > 50$ GeV for the leading jet). The two leading jets had to be acoplanar ($\Delta\phi(jet_1, jet_2) < 165°$), b-tagged, and have the energy fraction in the event $(E_T^{jet1} + E_T^{jet2})/(\Sigma_{jets}E_T)$ greater then 0.9. To reduce the contribution from $W \to l\nu$ decays, events with isolated electrons or isolated muons with $p_T > 15$ GeV were vetoed. The QCD multijet backround was suppressed with removal of events where the $\not{E}_T$ direction overlapped a jet in ϕ and events where the direction of $\not{E}_T$ is not aligned with the missing track $\not{p}_T$ (the negative of the vectorial sum of charged particles transverse momenta). Similar to the generation independent search, cuts on $\not{E}_T$ and H_T were optimized for the LQ signals of different masses.
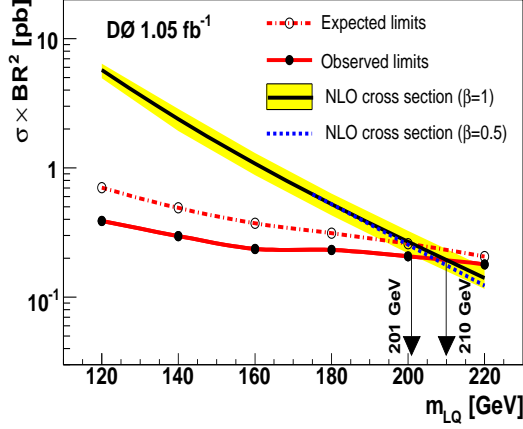
Figure 4: Observed (solid line) and expected (dash-dotted line) 95% C.L. limits on pair production of third generation leptoquarks decaying to τb. The yellow shaded band shows the uncertainty on the theoretical prediction. The dashed line indicates the threshold effect for the $t\nu_\tau$ channel.

Table III shows the number of data, estimated background (dominated by the events from top quark production and from $W/Z + b\bar{b}/c\bar{c}\ jets$, contribution of QCD multijet backround is negligible) and LQ events after all selections. No signal was observed and the 95% C.L. limits on charge 1/3 scalar third generation leptoquark production cross section were set (shown in Fig 5). Assuming $B(LQ \rightarrow \nu b) = 1$ a mass limit of 252 GeV was obtained. If $t\tau$ decay is possible then the limit is $M_{LQ} > 239$ GeV.

Table III $LQ\overline{LQ} \rightarrow \nu\bar{\nu}b\bar{b}$ analysis. Number of data, background and signal events after all selections for different LQ signals.

M_{LQ} GeV	$(\not{E}_T, H_T)$ GeV	Data	Background	Signal (acpt, %)
200	(130,220)	7	7.1±0.5±1.2	23.2±0.8±3.3 (2.1)
280	(150,240)	3	3.2±0.3±0.6	3.9±0.1±0.5 (3.4)

6. Summary

Searches for pair production of leptoquarks of all three generations were performed in 1–4 fb^{-1} D0 data samples. All presented analysis are in good agreement with the SM predictions. No leptoquarks signals were observed, and a set of 95% C.L. limits on LQ masses have been obtained improving previous Tevatron results. More details on the presented analyses can be found at [3].
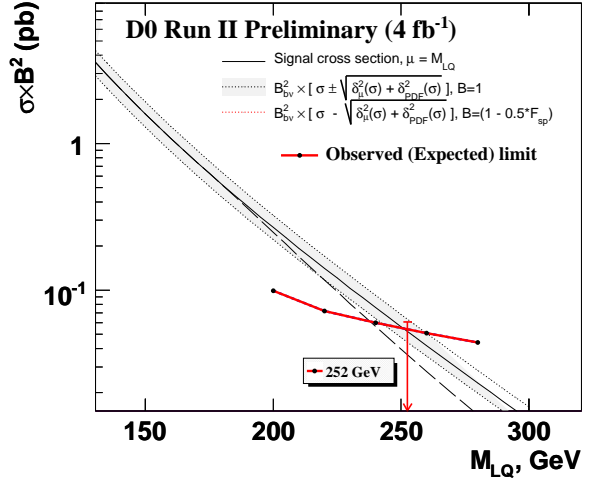

Figure 5: The 95% C.L. limit on $\sigma \times B^2_{b\nu}$ (points plus solid line) as a function of M_{LQ} for the pair production of third generation leptoquarks. The expected cross section limits are the same as the observed. The grey shaded band shows the PDF and the renormalization scale error bounds on the NLO production cross section (solid line) calculated for $\mu = M_{LQ}$. The long dashed line shows $\sigma * B^2(LQ \rightarrow \nu b)$ for the $B(\nu b) = B(t\tau) = 0.5$ times the phase suppression factor for the $t\tau$ channel.

References

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[3] http://www-d0.fnal.gov/Run2Physics/WWW/results/np.htm